An Information Note on Harmonic Issues and their impact on Customer connections

Note 1. (EirGrid 2013)

What is the purpose of this Information Note?

This Information Note summarises the customer's responsibility regarding harmonics issues on the Irish electricity system. It also covers both the background to the issue as well as the standards involved. EirGrid will continue to provide further communications on this subject as necessary.

In order to maintain a high quality, Power System any customer seeking to connect via, or in close proximity to, a high voltage underground cable should contact the System Operator (DSO or TSO) to discuss any possible implications for their project as early in the planning process as is possible. High voltage underground cable connections can introduce power-frequency resonance points to the local system. Any unwanted harmonic currents injected at these resonance points will be amplified and result in severe distortion to the local system voltage. It is particularly important that all details of such cable connections, internal networks and plant, including any reactive power devices, be communicated to the System Operators in a timely manner in order to assess and identify an optimal solution for all neighbouring applicants. All Pre-Energisation Data (PED) must be submitted at least 1 year prior to connection but detailed connection methods involving high voltage underground cable connections should be communicated earlier if possible. This minimises the risk of long lead times associated with potential mitigation solutions if harmonics issues are identified. Other details including project timelines, policies, methodologies and potential charging solutions will be communicated to customers as EirGrid continues to address these issues.

What does Power Quality mean?

"Power Quality" refers to the condition of the electrical supply as presented at a customer load. This is the most important power system feature after Security of Supply which ensures a continuous availability of power. Power Quality concerns any manifestation of voltage or current deviations that can result in the failure or mal-operation of customer equipment. Typically, the most pertinent parameters are associated with the voltage waveform. These include (a) the magnitude and balance of the three-phase voltages, (b) transient fluctuations and (c) individual and total voltage harmonics and inter-harmonics.

What are Power System Harmonics?

Harmonics are simply any signal or wave that occurs at a frequency that is an integer multiple of the fundamental 50 Hz sinusoidal voltage waveform. The net effect of these harmonics is that they combine with the voltage (or current) waveform and are superimposed onto it, thereby inflicting a distortion. This means that the smooth sinusoidal aspect of the 50Hz voltage (or current) waveform may be destroyed. Figure 1 below portrays this additive effect for a single phase and its detrimental impact on the 50Hz voltage (or current) waveform.

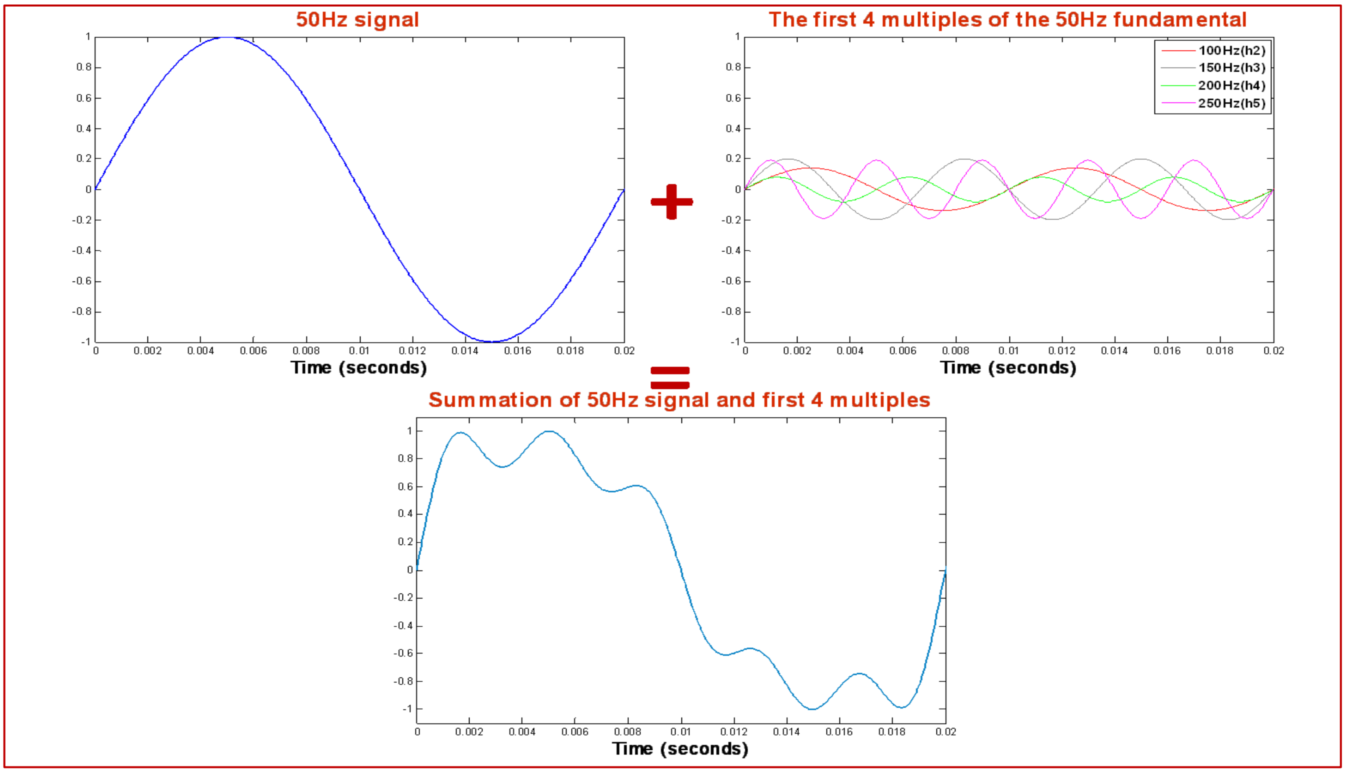

Figure 1 depicts the first four voltage harmonics and the resulting distortion which they would cause to a 50 Hz voltage (or current) waveform. Only the first 4 multiples denoting the 2nd, 3rd, 4th and 5th harmonics with varying magnitudes are shown here.

What are the sources of the Harmonics?

The principal cause of current harmonics on the power system is non-linear customer loads. A linear load is one which, when applied with a steady-state, single-frequency sinusoidal voltage results in the flow of a purely sinusoidal current of equal frequency and proportional magnitude. Such devices include incandescent light-bulbs and ovens and, as such, historically represented the majority of the domestic electrical demand on the power system. The current drawn is not directly proportional to the magnitude and/or phase of the voltage for non-linear loads. Therefore, non-linear loads result in the flow of transient or steady-state currents with frequencies other than that of the supplied steady-state, single-frequency sinusoidal voltage. These harmonic currents will interact with the system impedance and cause a harmonic voltage distortion.

Many types of power system devices result in the flow of distorted currents. A few of these are listed in Table 1. Specifically, all power electronic devices, switch-mode power supplies common in household and industrial appliances, and variable frequency drives are non-linear as they utilise current in abrupt short pulses. Plant with ferromagnetic cores such as power transformers, motors and generators may also promote harmonic currents by drawing non-sinusoidal current if they enter their magnetic saturation regimes. Devices that utilise arcing such as furnaces, welders and fluorescent lighting are also known harmonic current sources.

Power Electronics	ARC devices	Saturated ferromagnets
Power converters	*Fluorescent lighting*	*Transformers*
Variable frequency drives	*ARC furnaces*	*Motors*
DC motor controllers	*Welding machines*	*Generators*
Static var Compensators		
Power supplies, UPS and Battery Chargers		
Inverters		

Table 1: Recognized sources of Harmonic injections from customer installations.

Why are Harmonic problems becoming an increasing concern?

The increasing use of power electronics and converters (particularly for wind turbines) are injecting more harmonic currents onto the system.
The influx of more cables onto the network can exacerbate the problem by amplifying any harmonic injections present.

Harmonics are not a new phenomenon and have been an issue on AC power systems since their invention. As Transmission System Operator, and in-line with Grid Code requirements, EirGrid, continuously monitor the power system for the presence of power system harmonics. Power System Harmonics are an issue on every major power transmission system and EirGrid utilises international standards for harmonics. In addition, EirGrid are in discussions with a number of TSOs and internationally recognised experts regarding of measurement, modelling and mitigation strategies.

The increasing prevalence of power electronics on the Irish power system is directly contributing to the increased presence of harmonic currents and voltages. The power converters used in wind turbines are of particular concern, especially where they are located in isolated regions of the electrical network. The presence of harmonic currents even within IEC61000 standard limits may not be a problem, but if they are present and the local electrical network has a resonance around that harmonic frequency then a severe harmonic voltage may appear as well. This voltage distortion is experienced by all customers connected to the local electricity network and can have a detrimental impact on the performance and lifetime of connected devices.

Power converters, such as those found in battery chargers and Uninterrupted Power Supplies (UPS), electronic ballast lighting, inverters and variable frequency drives are intrinsic components of many large scale demand customers. These may influence harmonic voltages with respect to any harmonic currents produced at each frequency multiple. Although the harmonic injections of most consumer equipment is limited by IEC61000 standard, some significant customer loads may be in close proximity to other customers or cables which can have undesirable interactions.

The influx of more cables onto the network can exacerbate the magnitude of the voltage waveform distortion by changing the network impedance. Therefore cables may amplify any harmonic injections present. It is worth noting that the cables themselves do not introduce harmonics. Instead, they can serve to lower the frequency at which system resonance occurs due to the capacitance distributed along the cable length. Any harmonic current injections occurring at a resonant frequency can invoke a significant harmonic voltage which is undesirable. Cables are also subject to a phenomenon whereby the effective resistance of the conductor increases with frequency. This skin effect can limit the power transfer capability of the cable.

What are the consequences of Harmonic distortion?

Harmonics can damage users' and system equipment. They may also interfere with telecommunication. Harmonics cause higher losses through increased currents in the power system.

Harmonic related distortions can result in the failure or mal-operation of customer equipment and power system plant. The existence of harmonic currents imposes an ampacity limit on the magnitude of the customer load that can be served as they needlessly waste some of the current carrying capacity of the conductors. The additional harmonic currents also increase the total system current flowing. This has immediate consequences since higher losses are observed when power is converted to waste heat, due to the product of the conductor resistance and the current squared.

The presence of harmonic currents and voltages results in additional heating of power system plant. Generators, motors and transformers are susceptible to additional heating increased flux losses, which decreases the power capability and their lifetime. These magnetic eddy currents are proportional to frequency so higher harmonic orders imply higher currents flowing, thereby increasing the heating experienced by the plant and possibly shortening its lifespan. A number of harmonics can also place a rotational torque on motors which may require additional power to overcome. Some harmonic orders may also cause current to flow in the neutral wire which requires it to be oversized to avoid excessive heating. This wire provides a low impedance connection that carries current to ground for an item of plant to prevent the manifestation of spurious hazardous voltages.

Capacitors are often utilised on the power system for reactive power support and power factor correction. However, as their reactance is inversely proportional to frequency they provide a low-impedance path. Conversely, inductive reactance increases with frequency. There exists an impedance-frequency resonance point when the capacitive and inductive reactance is equal in a local network. Any small harmonic current injected at this parallel resonance point will result in large voltage harmonics and associated voltage distortion. The presence of harmonic currents or a potentially excessive voltage at a harmonic resonance point serves to dramatically shorten the life cycle of the capacitor bank.

Telecommunications interference is a much maligned result of unbalanced audio-frequency harmonics present in the power system. These may couple with neighbouring metallic communication circuits and excite unacceptable noise levels due to the appearance of spurious AC currents and voltages in the telecoms circuits. Exposure to harmonic distortions between 500Hz and 1200Hz (10^{th} to 24^{th} harmonic) are particularly problematic since this is the bandwidth utilised by voice telephony. Fiber networks are impervious to this noise since optical signals do not interact with electrical channels.

Most contemporary electronic circuits employ a triggering system to convert the AC voltage waveform to a usable dc power source. These rectifier devices often rely on detecting the zero-crossing of the x-axis of the AC voltage to determine the frequency of the system power supply. This timing signal detection may function incorrectly and misfire if the voltage waveform has undergone harmonic distortion since multiple crossings may occur. The potentially high frequencies associated with the distortion pattern can cause end-use consumer equipment to fail.

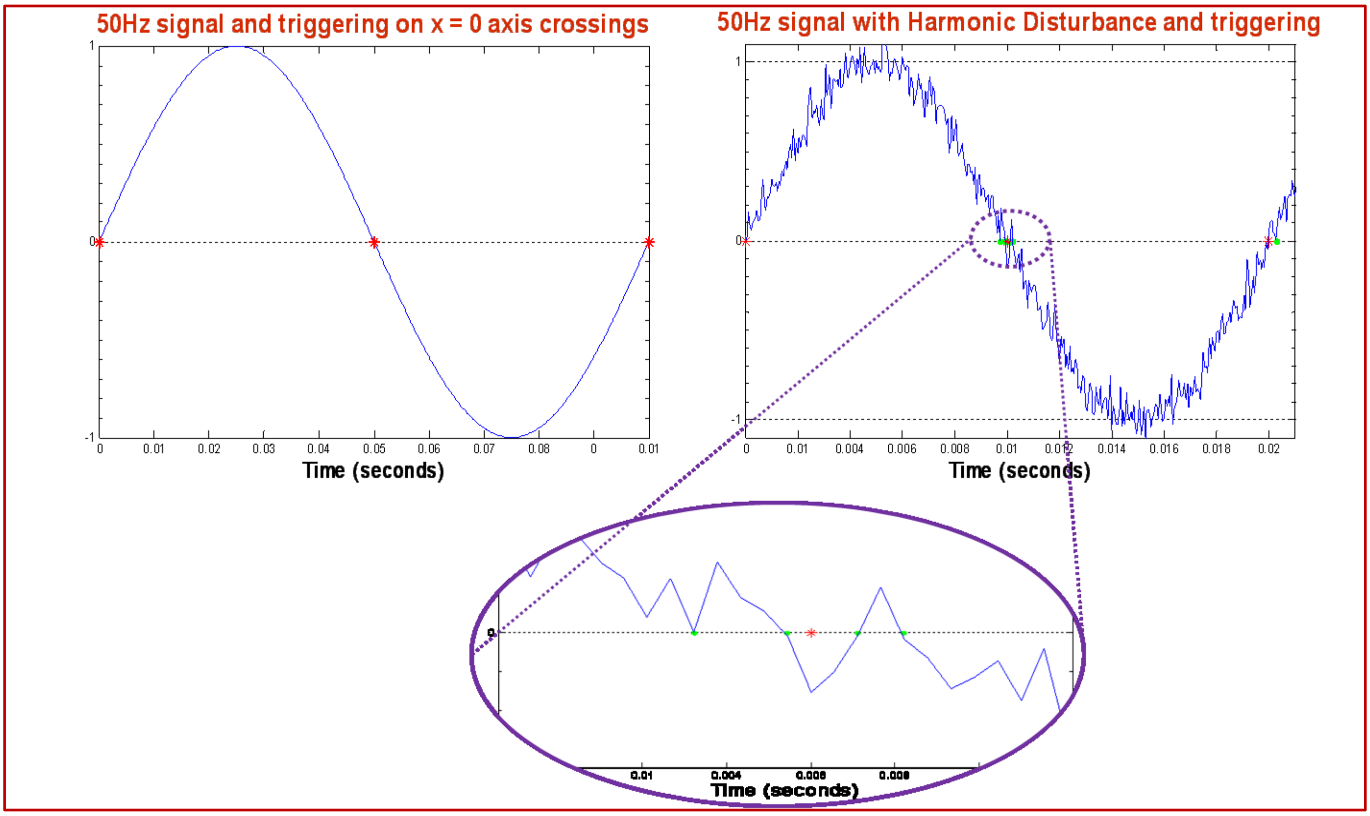

Figure 2 (left) portrays triggering as the sinusoidal voltage waveform crosses the x-axis, denoted by a red *. In the rightmost figure, the same waveform is subject to harmonic distortion. The zero-crossings are now shown by a green • but they do not necessarily coincide with the original 50Hz firing points and multiple points can occur in a short timeframe. For examples there are 4 such crossings in the 0.009 to 0.011 range, implying a frequency of 750Hz, but none overlap with the desired 50Hz crossing point at 0.01s.

What do the standards say?

> The customer is responsible for ensuring that their plant is compliant with the standards outlined in the Grid Code or Distribution Code

Both the Grid Code (CC10.13) and Distribution Code (DCC9.5.1) place the onus of responsibility on the user to ensure that their plant is compliant and does not result in the level of distortion or fluctuation of the supply voltage at their connection point to exceed that allocated to them. The distortion limits applicable are outlined in IEC/TR3 61000-3-6. These denote the total cumulative distortion permitted at the Point of Common Coupling for the combined contributions from all associated connections. Lower voltage limits are specified in the Distribution Code (DCC6.8.3) to ensure compliance with the CENELEC Standard EN 50160. An itemised allocation of spectral emissions for any customer can be determined on request from the relevant System Operator. This allocation details the maximum emissions permitted from a customer's site and will be less than those in the IEC/TR3 61000-3-6 planning standard since (1) other customers at the same location will be allocated a portion of the tolerated range for injections on a fair and appropriate basis and (2) a safety margin is retained for operational prudence and / or future developments. It is vital that customers advise the System Operator as early as is practicable in advance of any possible underground cable connection request for their project. Any applicants who fail to supply cable connection method details sufficiently early prior to energisation can prevent their project from being assessed until such time as appropriate data has been received. All Pre-Energisation Data must be submitted at least 1 year in advance of connection to the system. If any power quality issues are subsequently identified, this will impact on the applicant's project and may incur a delay to their connection to the power system until a suitable mitigation solution is in place.

What must customers do?

It is the customer's responsibility to ensure that their facility is Grid Code compliant. The System Operators will assist any customer seeking clarification of the harmonic voltage distortions permitted at their point of connection to the network. It is imperative that any customer seeking to modify their reactive power characteristic, be it through requesting a cable connection or modifications to their turbine types, internal network, transformers, filters or reactive power support, must communicate the updated parameters to the System Operator early in the connection process. All Pre-Energisation Data (PED) must be submitted to the appropriate System Operator at least 1 year prior to connection but it is recommended that detailed connection methods involving high voltage underground cable connections should be notified earlier if possible. This can minimise the customer's risk in the event of a harmonics issue being identified since any mitigation strategy may require a significant lead time to implement. This is beneficial to both parties since the System Operator may enhance their model and identify proposed limits at a sufficiently early stage. If a harmonics issue is identified, the customer will then be advised of such limits which may aid in their selection process for suitable turbine types and / or necessary filtering prior to any outlay of significant capital resources. In addition to harmonic emission limits, the System Operator will also provide impedance loci for the power system at the customer's connection point. Each of these loci is a discrete polygonal envelope which represents a bound on the network impedance for one or more harmonic frequencies. A number of impedance loci will be provided spanning the full range harmonic orders. These loci are formed by plots of reactance (X) vs resistance (R) and reflect the influence of numerous different configurations of the transmission system at those frequencies, including significant outages with a view to accounting for many of the feasible operational regimes. A customer's project may be prevented from connecting to the power system until such time that all appropriate harmonic limitation mechanisms are in place.

Once the customer has received their allocated limits and impedance loci (see sample data in Appendix 1), they must select appropriate turbines and any required filters to comply with their allotment at each harmonic frequency. The customer must then revert to the System Operator with their proposed solution. An overview of various solution strategies is given in Appendix 2. The supplied parameters may then be utilised to verify that the solution does not interact detrimentally with neighbouring customers. However, it is not the System Operators responsibility to endorse any proposals regarding harmonic compliance. A synopsis of the customer requirements above is given in Table 2 and Table 3 below.

Prior to receipt of Harmonic Injection Limits and Impedance loci
Contact the System Operator well in advance of any potential cable request modifications. (Early notice is advisable for high voltage UGC connections)
Notify the System Operator of turbine types or reactive power devices on site or any changes sought as early as possible. (All PED must be submitted 1 year in advance)

Table 2: Customer's responsibility in order to obtain harmonic limits

After obtaining Harmonic Injection Limits and Impedance loci from the System Operator, some or all of the following may be required
Purchase/Install turbines that have harmonic injections below the allocated limits at the specified frequencies
Install harmonic mitigation plant such as filters to reduce harmonic injections below acceptable levels at the specified frequencies
Communicate the parameters of the solution devices with the System Operator

Table 3: Customer's obligations after receiving harmonic limits

If you have any queries about harmonic issues can affect your project, please contact Customer Relations by emailing info@eirgrid.com.

Appendix 1: Sample limits and Impedance loci to be communicated to Customers by the System Operator

STATION X 110 kV
Harmonic Voltage Limits applying to plant and equipment of each customer at STATION X 110 kV node

Harmonic Order (multiple of 50Hz)	Allowed Voltage Distortion Resulting from Harmonic Emissions of All Installed Plant at STATION X 110 kV (in % of nominal 50 Hz voltage)		
	DSO Transformer* (*x* MW Generation Capacity)	Applicant 1 Gate A (*y* MW Capacity)	Applicant 2 Gate B (*z* MW Capacity)
2	0.1	0.1	0.2
3	0.1	0.1	0.2
4	0.2	0.4	0.5
5	0.2	0.4	0.5
6	0.2	0.4	0.5
7	0.2	0.4	0.5
8	0.2	0.4	0.5
9	0.1	0.2	0.4
10	0.1	0.1	0.2
11	0.2	0.4	0.5
12	0.2	0.4	0.5
13	0.2	0.4	0.5
14	0.1	0.1	0.2
15	0.1	0.2	0.4
16	0.2	0.4	0.5
17	0.1	0.1	0.2
18	0.1	0.2	0.4
19	0.1	0.1	0.2
20	0.2	0.4	0.5
21	0.1	0.2	0.4
22	0.2	0.4	0.5
23	0.2	0.4	0.5
24	0.1	0.2	0.4
25	0.1	0.2	0.4
26	0.1	0.2	0.4
27	0.1	0.1	0.2
28	0.1	0.2	0.4
29	0.1	0.2	0.4
30	0.1	0.2	0.4
31	0.2	0.4	0.5
32	0.1	0.1	0.2
33	0.1	0.1	0.2
34	0.1	0.1	0.2
35	0.1	0.1	0.2
36	0.1	0.2	0.4
37	0.1	0.1	0.2
38	0.1	0.2	0.4
39	0.2	0.4	0.5
40	0.1	0.2	0.4

Table 4: Sample Harmonic injection limits at the 110kV busbar in Station X. These have been calculated by EirGrid and fairly allocated with respect to the Maximum Export Capacity connected at each 110kV bay. *The limits apportioned to the DSO represent the cumulative injection tolerated on the HV side of the 110/38kV transformer. The DSO will reallocate these to the relevant applicants accordingly.

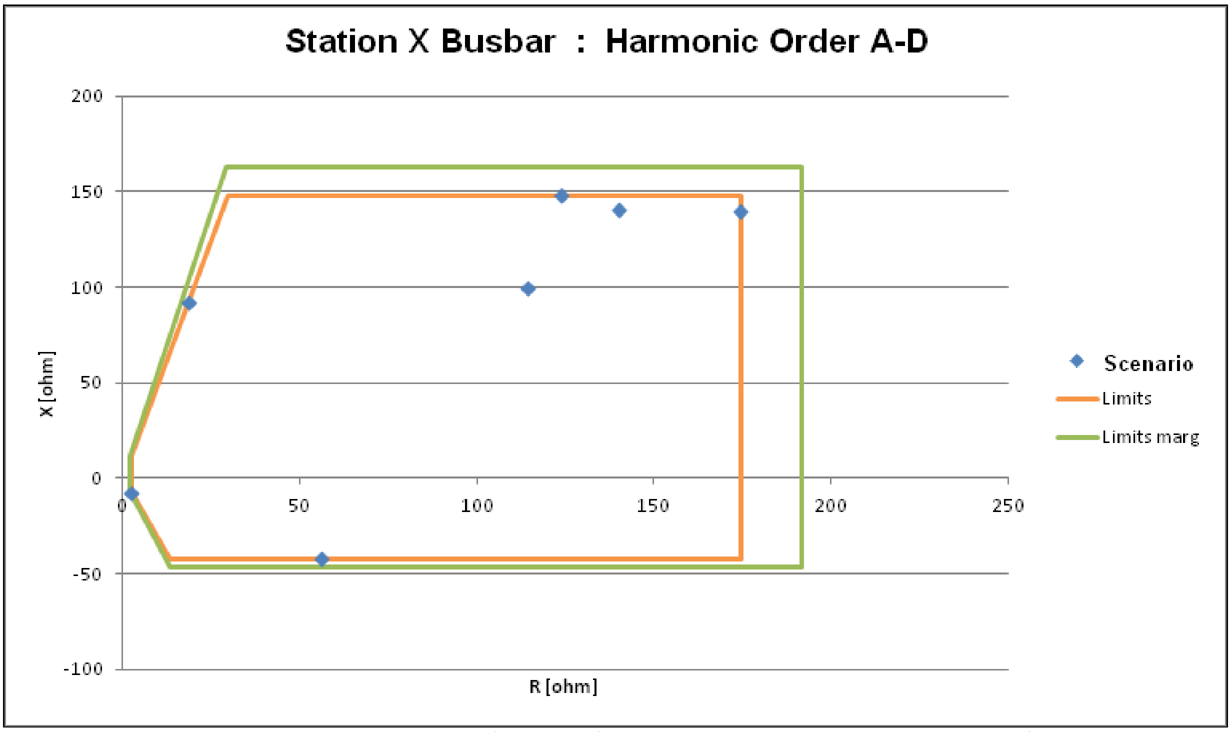

Figure 3 shows the Impedance loci for the first D harmonic orders. Each of the scenarios denotes a network configuration that was considered in the analysis covering all aspects of normal system operation from the most onerous Summer Night Valley minimum load case to the Winter Peak maximum demand scenario. The envelope captures the effects of alternate line flows, loadings and dispatches in the interim. The margin accounts for the retained overhead up to the Planning limits in IEC/TR3 61000-3-6 for future development and system safety.

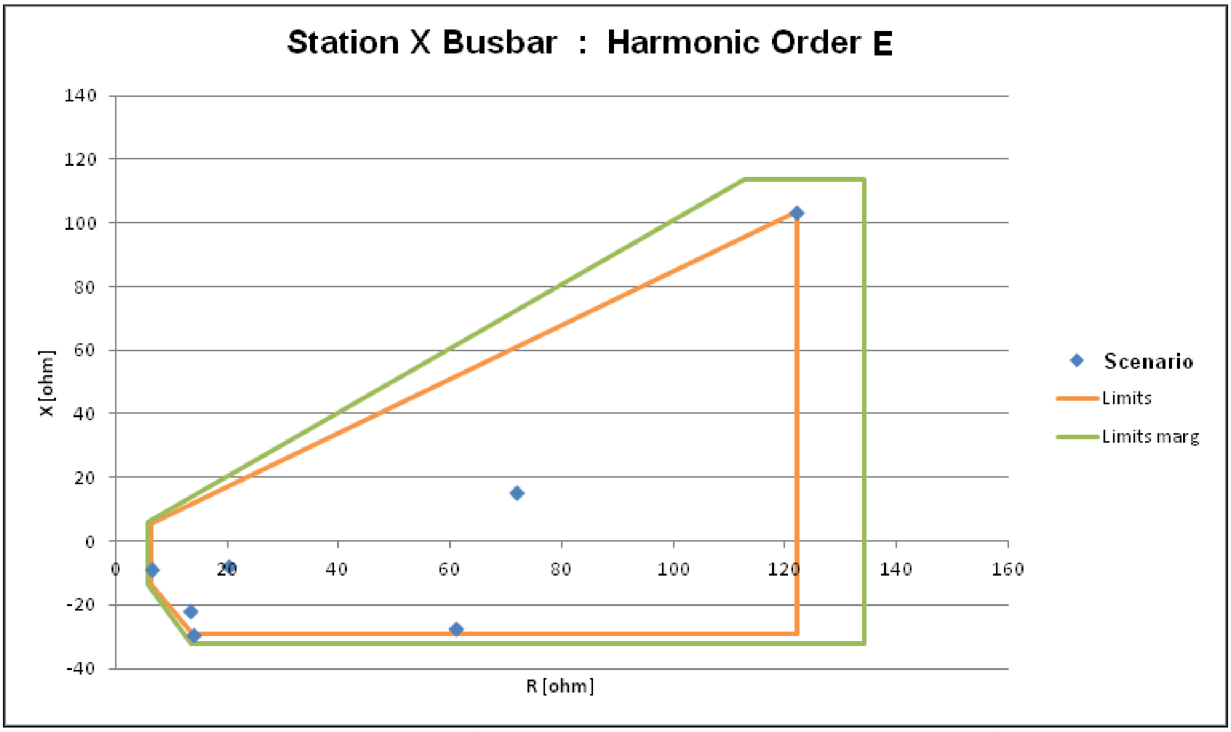

Figure 4 depicts the Impedance loci for the harmonic order *E*. It may be beneficial to describe a spectral region of concern with a single bound in order to accurately specify a filter without it being centred at an inopportune frequency.

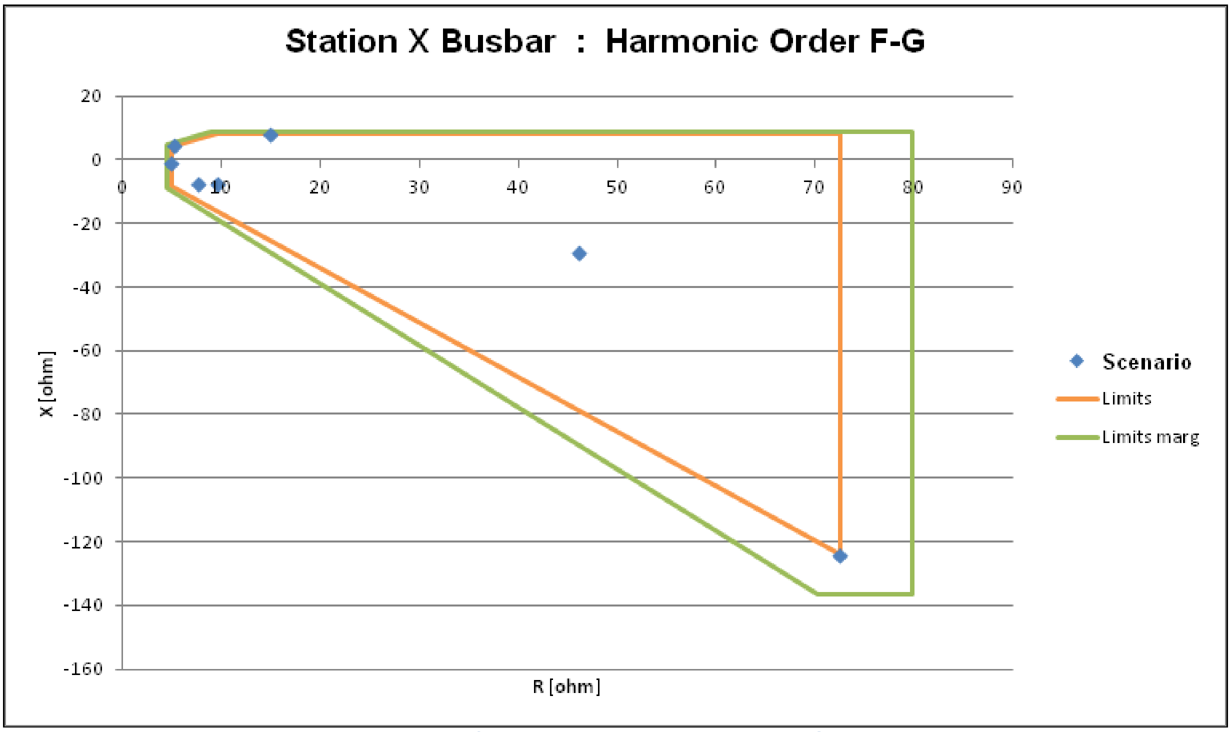

Figure 5 portrays the Impedance loci for the harmonic orders *F-G*.

Appendix 2: How are Harmonics Problems Mitigated?

There are a number of strategies to mitigate harmonic issues. However, the selection of a solution from all of the prescribed options is non-trivial. This is primarily due to interactions with neighbouring customers increasing the complexity of the analysis and uncertainty over the final connection method to be constructed. For example, if an applicant opts to connect via high voltage underground cable, they may introduce an impedance-frequency resonance point in the local network, which will limit the harmonic current injections for all contributing projects. These interactions become increasingly complex as other nearby applicants may also select cables as their preferred connection method. It is essential that all influencing applicants submit their project data to the System Operator, including details of their cable connections, internal networks and plant including reactive power devices, well in advance of their target connection date to ensure sufficient time to assess and identify an optimal solution for their region of influence. Although all other Pre-Energisation Data should be communicated to the appropriate System Operator no later than 1 year prior to connection, it is recommended that any details of underground cable connections be notified earlier if possible.

There is no predetermined mitigation proposal or associated order of preference, as each option must be analysed in a case specific context to identify the most cost-effective and enduring solution. It is also important to note that any future connection method modification may require a revision of the solution to be applied. There is a possibility that no single viable approach may be identified and a combination of the following mitigation strategies will be required. The responsibility for each option can reside with the relevant System Operator or the customer or both (denoted in parentheses below), depending on the outcome of a cost-benefit analysis.

System Reinforcement **(System Operator)**

This option involves increasing the strength of the power system in the region where the applicant(s) is located. Typically, this approach alters the system impedance observed at each harmonic order, effectively allowing any injections that manifest close to a parallel resonance point to be tuned up the frequency spectrum by means of an increased inductance. The reinforcements required to modify the system impedance can involve the commissioning of additional power transformers or construction of new overhead lines. The commissioning of this plant can involve significant lead-times and costs. Furthermore, it is important that the permanent connection methods associated with all influencing projects must be known in advance of selection of this strategy. This is to account for the change in system impedance with the addition of new or expanded customer internal electrical networks and devices or the construction of new power system infrastructure

Isolation transformers (System Operator / Customer)

Some higher frequencies can be attenuated by certain transformer configurations. This is particularly true for triplen harmonics (those that are odd multiples of three) since any associated zero sequence harmonic currents will flow to ground through the neutral of a wye-delta transformer providing the currents are balanced and in-phase. This solution is not applicable for all harmonic orders as the harmonic currents may not be in-phase with each other and will therefore pass through the transformer. The commissioning of a transformer for this solution may involve a long lead-time and/or incur significant expense depending on whether the transformer is located at a transmission system voltage level or as a step-up or generator transformer on the distribution system or internal customer network.

Harmonic Injection limitation (Customer)

This is the simplest mechanism for controlling the system harmonic distortion. If minimal harmonic currents are injected onto the system, there will be a diminished magnitude for the associated harmonic voltage distortion arising from these currents interacting with the system harmonic impedance. These injection limits will be calculated by the System Operators and communicated to the customer after the customer submits the appropriate project data and requests analysis to ensure compliance with the IEC-61000-3-6 standard and the Grid or Distribution Code. This mitigation strategy compliments each of the alternate options as it does not interact with any plant thereby potentially further altering the system impedance. It is worth noting that selecting an alternate turbine type may facilitate compliance with the imposed harmonic limits without requiring any additional measures.

Passive Filter (System Operator / Customer)

There are numerous configurations associated with this mitigation approach ranging from a simple inductive reactor to dampen the harmonics to complex multi-stage filters tuned to block multiple harmonic frequencies. The fundamental mechanisms of harmonic filtering devices requires the inductive and capacitive components to resonate at select frequencies, thereby presenting a virtual short-circuit or low impedance path to ground for any injected harmonic currents at that or nearby harmonic orders. This implies that the harmonic voltage at the filter's resonant frequency will be negligible whilst still maintaining the desired system impedance, and hence voltage, at the fundamental 50Hz frequency. Harmonic filters may equally be utilised to counteract the resonances imposed by uncontrolled capacitances presented by local cables by selectively tuning the resonant points away from harmonic injections as required.

Filters may present a cost-effective solution in many cases depending on the number and spectral range of the harmonics to be eradicated, although, they can add an additional level of complexity to the operation of the system. Such filters are designed based upon a particular system impedance and if that impedance changes due to new power system infrastructure the filter may lose effectiveness and permit excessive harmonic emissions onto the power system. As impedance values vary by season due to changes to the generation portfolio dispatched and associated network configurations, passive filters may not be a future-proof solution unless strict design criteria are employed.

Active Filter (System Operator / Customer)

This is a relatively recent development for controlling any harmonic distortion. Active filters are derived from passive versions and offer similar functionality except that they can account for variation of the system impedance over time. As the reactors and capacitance automatically retunes to attenuate select frequencies, the filter offers a stable solution for any harmonic problem. However, this may be an expensive approach since active filter technology is still very much in its infancy. Further considerations must be given to possible complex interactions between neighbouring active filters as any changes to the impedance initiated by one filter may automatically result in the retuning of another device in the locality, realising a circular effect.

Overhead Line (System Operator / Customer)

Underground cables typically exhibit characteristics that result in resonance at low order (5^{th} – 7^{th}) harmonic injections. Overhead lines do not typically exhibit such resonances. Harmonic injection limits will still apply to applicants connecting via overhead lines to ensure minimal high frequency currents are present at higher order harmonics or if the background harmonic distortion is already significant at a node.

Appendix 3: References

EirGrid Grid Code
http://www.eirgrid.com/operations/gridcode/

ESB Distribution Code
http://www.esb.ie/esbnetworks/en/about-us/our_networks/distribution_code.jsp

IEC/TR 61000-3-6 (ed2.0) Standard on Electromagnetic compatibility (EMC)
Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems
http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/39088